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ASSESSMENT OF FLORAL STAGE-SPECIFIC FROST INJURY UNDER CONTROLLED CONDITIONS AND EVALUATION OF MITIGATION SYSTEMS IN A'FUJI' APPLE ORCHARD

Je-Chang Lee[1][2] and Jae-Yun Heo[1]*

[1]Department of Plant Science, Gangneung-Wonju National University, Gangneung 25457, Republic of Korea
[2]Horticultural Crops Research Group, Gangwon State Agricultural Research & Extension Service, Chuncheon, Republic of Korea
*Corresponding Author's Email: jyheo@gwnu.ac.kr

ABSTRACT

In recent years, the apple cultivar 'Fuji' has frequently suffered frost injury during the flowering period in Korea due to climate change, posing serious challenges to yield stability. This study evaluated the frost tolerance of 'Fuji' flower organs across developmental stages and assessed the field applicability of wind machines and sprinklers as frost protection measures. Controlled freezing tests using floral samples from M.9-grafted trees demonstrated that frost sensitivity increased as development progressed, with injury evident from –4 °C at the tight cluster stage and complete necrosis observed at –2 °C during full bloom. To assess practical effectiveness, an on-farm trial was conducted during a natural frost event in 2021. The wind machine increased orchard air temperature by up to 2.2 °C but had minimal effect on humidity, whereas the sprinkler system moderately raised temperature and markedly elevated relative humidity by more than 10%. These modifications reduced floral injury rates to 17.8% and 19.5%, compared with 28.2% in the untreated control. These findings provide quantitative evidence that both technologies can substantially mitigate frost injury. By demonstrating significant reductions in floral damage under natural conditions, this study underscores their potential to enhance yield stability and strengthen the climate resilience of apple production in frost-prone regions.

Keywords: Climate change, Field, Flower, Freezing, *Malus x domestica*

INTRODUCTION

With an annual production of 97.3 million tons in 2023, apples (*Malus domestica* Borkh.) rank as the third most widely produced crop worldwide, underscoring their substantial economic importance within the horticultural sector (Navarro Villa, 2025). Globally, climate change has brought profound changes to apple production systems. In Korea, it has intensified the frequency of high temperatures and tropical nights in traditional mid- to low-latitude apple-growing regions, creating challenges for maintaining fruit quality (Lee *et al*., 2023a). Consequently, apple cultivation is increasingly shifting toward higher-latitude areas such as Gangwon State, where relatively cooler conditions offer more favorable environments for production. However, climate change has also advanced apple blooming, thereby heightening the global risk of frost damage to floral organs during early spring (Pfleiderer *et al*., 2019; Chen *et al*., 2024). Frost events during flowering reduce fruit set, increase fruit drop, and result in misshapen or poor-quality fruit, ultimately lowering both yield and marketability. In Korea, such early blooming has already led to substantial frost-related losses; in 2023, for example, frost injury caused nearly a 30% reduction in national apple production (KREI, 2024). A greater challenge is that high-latitude regions are especially vulnerable to low spring temperatures, which increase the likelihood of floral organ damage from late frost events (Zebro *et al*., 2023). Therefore, developing effective frost mitigation strategies is imperative to ensure the sustainability and resilience of apple production in Korea.

Szalay *et al.* (2019) demonstrated that frost tolerance varies by both floral developmental stage and cultivar. Moreover, frost sensitivity is influenced by acclimation conditions, which can vary significantly depending on the local environment and management practices. Thus, identifying the developmental stages during which major commercial cultivars exhibit reduced frost tolerance is essential for implementing effective mitigation strategies in Korea's emerging apple-producing regions. Currently, 'Fuji' accounts for approximately 62.7% of the nation's total apple cultivation area and is the primary cultivar planted in high-latitude zones projected to become core production regions in the coming decades (Lee *et al*., 2023b).

Ensuring yield stability of ‘Fuji’ in these regions necessitates a detailed understanding of frost tolerance thresholds across its floral developmental stages and the adoption of effective protective technologies. We hypothesize that frost tolerance differs significantly across floral stages and that the efficacy of sprinkler and wind machine systems depends on local orchard conditions. While frost sensitivity has been studied in other regions, no integrated study has combined physiological threshold assessment with on-farm evaluation of frost protection systems in high-latitude Korean orchards. Linking these two aspects is essential: knowledge of floral sensitivity guides the timing and necessity of interventions, while evaluation of protection systems determines their practical applicability. This study therefore aims to (1) determine the critical frost tolerance thresholds of ‘Fuji’ flowers, and (2) preliminarily evaluate the feasibility of sprinkler and wind machine systems under on-farm conditions in Korea’s high-latitude orchards. The scope is limited to initial threshold characterization and pilot-scale field trials, providing a foundation for future large-scale adoption and refinement of frost mitigation strategies.

MATERIALS AND METHODS

Assessment of floral stage-specific frost injury under controlled conditions: This study was conducted using mature ‘Fuji’ apple trees cultivated in a high-latitude region of Korea to determine critical low-temperature thresholds for frost injury across distinct floral developmental stages. Controlled freezing experiments were carried out over two consecutive years (2020–2021) at the experimental orchard of the Gangwon State Agricultural Research and Extension Services, located in Chuncheon, Gangwon State, Korea. The plant material consisted of five 8-year-old ‘Fuji’ apple trees grafted onto M.9 rootstock, trained in a slender spindle system, and spaced 3 m between rows and 2 m within rows. Due to the limited availability of trees suitable for destructive sampling, the experimental design was restricted to a narrow range of floral developmental stages over the two years. In the 2020 experiment, floral samples were collected at three key developmental stages: silver tip, tight cluster, and full bloom. For each temperature treatment, ten fruiting branches, approximately 20 cm in length and of similar thickness, were excised from tree shoots located between 1.0 and 1.6 m above ground level and immediately transferred to a low-temperature incubator (Panasonic, Japan) for controlled freezing. Freezing temperatures were established with reference to Szalay *et al.* (2019). Accordingly, the following temperature treatments were imposed: –2, –4, –6, and –8 °C at the silver tip stage; 0, –1.5, –3.0, and –4.5 °C at the tight cluster stage; and 0, –1, –2, and –3 °C at the full bloom stage. For each experimental temperature, additional treatments of 1, 2, and 3 hours of exposure were prepared to examine the response to different durations of freezing stress. Following freezing treatment, samples were held at room temperature for 12 hours to allow for uniform recovery before frost injury assessment.

Based on preliminary results indicating increased sensitivity at advanced stages, the 2021 experiment focused on the tight cluster, full pink, and full bloom stages. Temperature treatments included –1°C, –2°C, –3°C, –4°C, and –5°C, each applied for a fixed duration of 4 hours. The experiment followed a completely randomized design (CRD). For each treatment, ten spurs were used, and each spur was considered an independent replication. Since the number of flowers per spur was not uniform, frost injury was quantified as the proportion of visibly necrotic flowers relative to the total flower number within each spur (Lee *et al.*, 2025).

Field evaluation of frost protection systems: To assess the effectiveness of frost protection systems under natural conditions, a field experiment was conducted on April 14, 2021, at a commercial orchard located in Bangsan-myeon, Yanggu-gun, Gangwon State. The orchard consisted of 7-year-old ‘Fuji’ trees on M.9 rootstock, similarly trained in a slender spindle system. The study compared the effectiveness of a wind machine and a sprinkler system in mitigating frost injury of floral organs at the tight cluster stage. The experiment was conducted as a completely randomized design (CRD). Each treatment consisted of nine trees randomly assigned within the orchard, and treatment plots were separated by buffer rows to avoid cross-treatment effects. The sprinkler system was equipped with nozzles calibrated to deliver 70 L/h, based on optimization trials conducted before the experiment. The wind machine had a coverage area of approximately 2,640 m². For the wind machine treatment, trees were sampled at distances of 5 m, 15 m, and 30 m from the machine (three trees per distance), and results were averaged. Environmental conditions, including ambient air temperature and relative humidity, were recorded at 30-minute intervals between 3:30 AM and 8:00 AM using a data logger (H21-USB; HOBO Data Loggers, MA, USA) connected to a temperature/humidity sensor (S-THB-M002; HOBO Data Loggers, MA, USA). Floral samples for frost injury assessment were collected one week after treatment from four randomly selected shoots at a height of approximately 1.5 m per tree. Frost injury was expressed as the proportion of visibly necrotic flowers. Each sampled shoot was treated as an individual replicate in statistical analysis.

Statistical analysis: All statistical analyses were performed using SPSS software (IBM Corp., NY, USA). Among the measured variables, values that allowed mean comparisons were analyzed using either one-way or two-way analysis of variance (ANOVA), depending on the experimental design. For one-way ANOVA, when significant differences among treatments were detected ($p < 0.05$), mean separations were conducted using Duncan's multiple range test, and results are presented with different letters to denote significant differences. For two-way ANOVA, the significance of main effects and their interaction was assessed, and results are presented using significance indicators ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$). When interaction effects were significant, additional mean comparisons were performed where appropriate.

Lethal temperature values resulting in 10%, 50%, and 90% frost injury (LT_{10}, LT_{50}, and LT_{90}, respectively) were estimated using probit analysis conducted in R (R Core Team, Vienna, Austria).

RESULTS

The first-year controlled freezing experiment demonstrated a clear, specific pattern in frost tolerance of 'Fuji' apple floral organs (Table 1). Regardless of treatment combination, overall floral mortality increased as freezing duration was prolonged and as exposure temperature decreased. However, the degree of sensitivity varied markedly across developmental stages. At the silver tip stage, necrosis was first detected at –4 °C but remained relatively limited. Even at –6 °C, short exposures of 1–2 h induced only modest injury, comparable to the damage observed at –4 °C. In contrast, exposure to –8 °C consistently resulted in >50% mortality regardless of duration, indicating a critical injury threshold at this stage. Sensitivity increased substantially by the tight cluster stage: more than half of flowers were killed after 3 h at –3 °C, and complete necrosis occurred following > 2 h of exposure at –4.5 °C. At the full bloom stage, flowers were extremely susceptible; visible injury occurred even at –2 °C, while 1 h at –3 °C caused 73.5% mortality and 3 h led to complete loss. Analysis of mean survival values indicated that temperature significantly affected mortality across all floral stages, whereas duration effects were statistically evident only at the silver tip stage. Two-way ANOVA confirmed these patterns: at the silver tip stage, both temperature and duration significantly influenced mortality, with a strong interaction between the two factors. At full bloom, mortality was almost exclusively governed by temperature, with neither duration nor its interaction exerting significant effects.

Interestingly, at the tight cluster stage, mean values suggested that duration alone was not significant; however, the two-way ANOVA revealed significant main effects of both temperature and duration, as well as a significant interaction. This indicates that, despite weaker differences in stage-averaged means, both factors remained important determinants of mortality at this stage.

The second-year freezing experiment, conducted from the tight cluster to the full bloom stage, further substantiated the stage-dependent patterns of frost tolerance observed in the first year (Table 2). At the tight cluster stage, survival was 100% at –1 °C but progressively decreased to 88.65%, 39.86%, 6.87%, and 0% at –2, –3, –4, and –5 °C, respectively. At the full pink stage, no injury was detected at –1 °C; however, survival declined to 54.85% at –2 °C and 1.25% at –4 °C. By the full bloom stage, flowers were unaffected at –1 °C but exhibited > 50% mortality at –2 °C, with complete necrosis at –4 °C and below. These results clearly demonstrated an increasing susceptibility with floral development, following the order: tight cluster > full pink > full bloom. Consistently, mean survival decreased sharply as temperature declined, and significant stage-specific variation was evident. Two-way ANOVA confirmed that both developmental stage and temperature significantly influenced survival, with a strong interaction between the two factors ($p < 0.001$), indicating that floral stage and freezing intensity jointly determined injury outcomes.

To further quantify critical thresholds of frost sensitivity, logistic regression analyses were used to estimate LT_{10}, LT_{50}, and LT_{90} values (Table 3).

LT_{10} values ranged from –1.99 °C at the tight cluster stage to –1.36 °C at full pink, reflecting the onset of measurable injury. LT_{50} values ranged from –2.86 °C (tight cluster) to –1.99 °C (full bloom), and LT_{90} values from –3.73 °C (tight cluster) to –2.37 °C (full bloom). Although LT_{10} at full bloom was occasionally higher than at full pink, LT_{50} and LT_{90} were consistently lower, clearly demonstrating that full bloom represents the most frost-sensitive stage of floral development.

Field trials under naturally occurring frost conditions further supported these results (Table 4, Fig. 1). Minimum air temperature in the untreated control plot declined to –1.8 °C at 6:00 AM before rising to 3.6 °C by 8:00 AM. Both protection systems elevated orchard temperatures relative to the control: sprinklers by 0.6 °C at 6:00 AM and 1.3 °C at 8:00 AM, and wind machines by 0.9 °C and 2.2 °C, respectively.

Relative humidity was inversely related to temperature (Table 5). Sprinklers increased humidity by 3.2% at 6:00 AM and 10.1% at 8:00 AM, whereas wind machines produced negligible changes (+0.5% and –0.1%).

Frost injury assessments revealed significant reductions under both treatments (Fig. 2). The sprinkler-treated plot recorded a 19.5% injury rate, an 8.7 percentage point reduction compared with the control (28.2%). The wind machine-treated plot showed a 17.8% injury rate, corresponding to a 10.4 percentage point reduction. Within the wind machine plot, injury rates were similar across distances from the fan, ranging from 16.8% (15 m) to 19.1% (30 m), indicating relatively uniform protection. Overall, both wind machines and sprinklers effectively reduced frost damage by modifying orchard microclimate.

Table 1. Frost injury rate (%) in floral organs as affected by the duration of freezing exposure across major flowering stages (2020).

Silver tip stage					
Duration/temperature	-2	-4	-6	-8	Means (Duration)
1h	0.00d	3.67d	19.67c	53.34b	19.17B
2h	0.00d	17.01c	24.34c	69.66a	27.75AB
3h	0.00d	17.34c	43.33b	71.34a	33.00A
Means (Temperature)	0.00D	12.67C	29.11B	64.78A	
Duration (A)	***				
Temperature (B)	***				
A × B	*				
Tight cluster stage					
Duration/temperature	0	-1.5	-3	-4.5	Means (Duration)
1h	0.00d	0.00d	28.33c	65.67b	23.50^{ns}
2h	0.00d	2.00d	39.16c	100.00a	35.29
3h	0.00d	2.50d	60.67b	100.00a	40.79
Means (Temperature)	0.00D	1.50C	42.72B	88.56A	
Duration (A)	Ns				
Temperature (B)	***				
A × B	**				
Full bloom stage					
Duration/temperature	0	-1	-2	-3	Means (Duration)
1h	0.00e	2.00de	23.33cd	73.50b	24.71^{ns}
2h	0.00e	4.00de	36.67c	77.33b	29.50
3h	0.00e	4.00de	43.00c	100.00a	36.75
Means (Temperature)	0.00e	3.33c	34.33b	83.61a	
Duration (A)	Ns				
Temperature (B)	*				
A × B	**				

Means with different letters (small case letters for interactions and capital letters for individual effects) are statistically different from each other by Duncan's multiple range test at p<0.05.

*** = p<0.001, ** = p<0.01, * = p<0.05, ns = not significant.

Table 2. Survival rate (%) of floral organs under artificial frost conditions at key floral developmental stages (2021).

Flowering stage	**-1°C**	**-2°C**	**-3°C**	**-4°C**	**-5°C**	**Means (Stages)**
Tight cluster stage	100.00a	88.65a	39.86e	6.87g	0.00h	47.08A
Full pink stage	100.00a	54.85c	16.18f	1.25gh	0.00h	34.46AB
Full bloom stage	100.00a	47.06d	1.65gh	0.00h	0.00h	29.74B
Means (Temperature)	100.00A	63.52B	19.23C	2.71D	0.00D	
Floral developmental stage (A)	***					
Temperature (B)	***					
A × B	***					

Means with different letters (small case letters for interactions and capital letters for individual effects) are statistically different from each other by Duncan's multiple range test at p<0.05.

*** = p<0.001.

Table 3. Floral developmental stage-dependent lethal temperatures (ºC) in ‘Fuji’ apple

Flowering stage	LT$_{10}$	LT$_{50}$	LT$_{90}$
Tight cluster stage	-1.99b	-2.86c	-3.73c
Full pink stage	-1.36a	-2.22b	-3.08b
Full bloom stage	-1.60ab	-1.99a	-2.37a

Mean separation within each column by Duncan’s multiple range test, 5% level.

LT$_{10}$, LT$_{50}$, and LT$_{90}$ represent the lethal temperatures (ºC) at which 10%, 50%, and 90% of flowers were killed, respectively.

Table 4. Temperature (ºC) changes associated with the application of frost mitigation systems in the orchard

Treatment / Time	3:30	4:00	4:30	5:00	5:30	6:00	6:30	7:00	7:30	8:00
Control	0.4	-0.2	-0.5	-1.1	-1.2	-1.8	-1.5	-0.9	-0.3	3.6
Sprinkler	0.5	0.0	-0.2	-0.9	-0.7	-1.1	-1.1	-0.7	-0.2	2.3
Wind machine	0.9	0.6	0.2	-0.5	-0.7	-0.9	-1.1	-0.8	-0.2	1.4

Table 5. Humidity (%) changes associated with the application of frost mitigation systems in the orchard

Treatment / Time	3:30	4:00	4:30	5:00	5:30	6:00	6:30	7:00	7:30	8:00
Control	86.9	88.0	87.1	88.9	89.4	90.5	90.5	90.1	89.0	72.7
Sprinkler	91.0	91.5	90.9	91.9	92.4	93.7	93.6	93.0	92.7	82.8
Wind machine	85.3	85.3	86.3	89.0	89.4	91.0	91.3	91.0	90.2	72.6

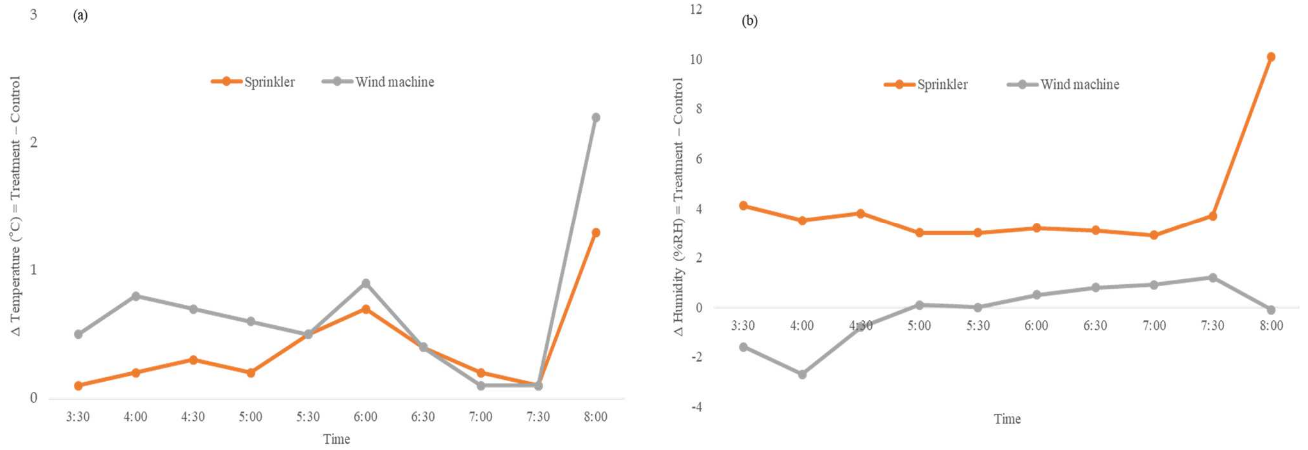

Fig. 1. Impact of sprinkler and wind machine applications on (a) temperature and (b) humidity, shown as deviations (Δ) relative to the untreated control. Δ Temperature (°C) = Treatment – Control; Δ Humidity (%RH) = Treatment – Control.

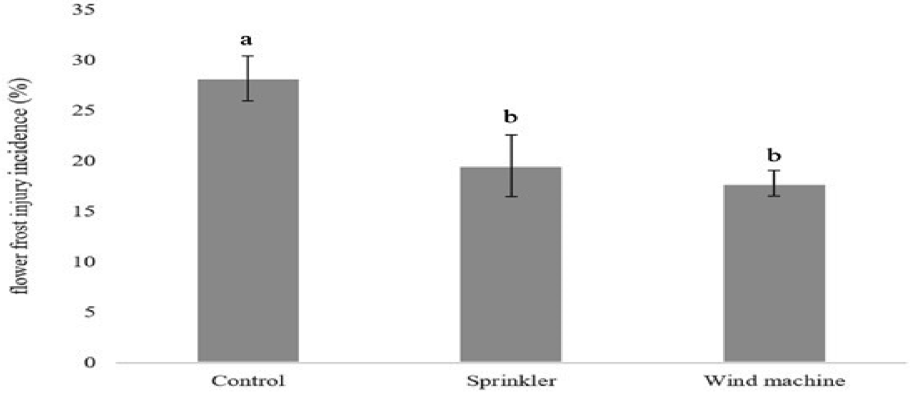

Fig. 2. Effect of frost mitigation systems on the incidence of flower frost injury (%). Mean separation within each bars by Duncan’s multiple range test at p<0.05.

DISCUSSION

This study provides clear evidence that the frost tolerance of 'Fuji' apple floral organs declines progressively as development advances. Results from the first year revealed that the effect of freezing stress on apple flowers is highly stage-dependent. At the silver tip and tight cluster stages, flower survival was significantly influenced not only by temperature and exposure duration but also by their strong interaction, suggesting that early floral tissues retain a certain buffering capacity against transient frost events. In contrast, at the full bloom stage, flower survival was determined almost exclusively by temperature, with no significant interaction with duration, indicating that once flowers reach anthesis, even brief exposure to critical thresholds can result in severe injury. Building on these findings, experiments focusing on the more frost-sensitive stages (tight cluster through full bloom) provided quantitative thresholds that further confirmed this trend. LT_{50} decreased from –2.86 °C at the tight cluster stage to –1.99 °C at full bloom, and LT_{90} shifted from –3.73 °C to –2.37 °C, indicating a rapid loss of resilience within a short developmental period. These values demonstrate that even relatively mild frost events near –2 °C—conditions commonly encountered in early spring at high-altitude Korean orchards—are sufficient to cause substantial floral mortality. Together, these results highlight critical windows of vulnerability during which protective measures are most urgently required. The stage-specific decline in tolerance is consistent with developmental and metabolic changes previously described in deciduous fruit crops (Rodrigo, 2000; Melke, 2015). The transition from silver tip to tight cluster coincides with increases in tissue hydration and decreases in membrane stability, processes that enhance susceptibility to extracellular ice formation and cellular rupture (Pearce, 2001). While studies in other crops have linked frost tolerance to alterations in carbohydrate, amino acid, and lipid metabolism (Kaya *et al*., 2021; Mao *et al*., 2022; Kaur *et al*., 2024), such mechanistic understanding remains limited in apple. Our results, combined with these earlier reports, suggest that both metabolic and structural factors interact with developmental stage to shape floral frost sensitivity, underscoring the need for targeted physiological and molecular investigations in apple.

Field trials conducted under natural frost conditions demonstrated that both wind machines and sprinkler systems reduced floral injury by 8–10 percentage points compared with the control. Although the wind machine produced a greater warming effect (+2.2 °C at 8:00 AM), the sprinkler system conferred additional benefits through increased relative humidity, potentially reducing radiative heat loss and desiccation stress. The uniform protection observed across distances from the wind machine further supports its effectiveness under mild frost conditions. These mechanisms are consistent with prior studies showing that wind machines disrupt temperature inversions to draw warmer upper air downward (Ribeiro *et al*., 2006; Dai *et al*., 2024), while sprinklers protect through latent heat release and humidity enhancement (Olszewski *et al*., 2017; Pan *et al*., 2024). Importantly, both systems provided comparable levels of protection in this trial, suggesting that multiple strategies may be viable for orchard frost management. However, each method carries distinct advantages and limitations, requiring careful consideration in practice. Wind machines impose relatively high installation and operational costs, whereas sprinklers are less costly to operate and may therefore be more attractive to growers. In high-altitude Korean orchards, however, some sites are located in mountainous regions where securing sufficient water resources is difficult, which can restrict the use of sprinkler systems. Therefore, the choice of a frost protection strategy must carefully balance biological efficacy with logistical feasibility. Moreover, because this study was limited to a single frost event near the green tip stage, additional trials across different seasons, floral stages, and frost severities are needed. Such research will refine system activation thresholds, optimize operational protocols, and improve understanding of long-term cost-effectiveness.

Conclusions: This study showed that the frost tolerance of 'Fuji' apple flower organs declined sharply as development progresses, highlighting critical windows of vulnerability. Field trials confirmed that wind machines and sprinkler systems can effectively mitigate frost injury by altering orchard microclimates. Growers in frost-prone areas, particularly in the high-altitude regions of Korea that are increasingly vulnerable to climate-induced frost events, should adopt these technologies strategically during sensitive stages to reduce yield loss. Future research should focus on elucidating the physiological and molecular mechanisms underlying floral frost sensitivity, which will support the development of more targeted and efficient protection strategies.

Conflicts of Interest: The authors declare no conflict of interest.

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REFERENCES

Chen, R., J. Wang, Y. Li, R. Bai, M. Huang, Z. Zhang, L. Zhao, Z. Qu,and L. Liu (2024). Higher risk of spring frost under future climate change across China's apple planting regions. Eur. J. Agron. 159: 127288. doi.org/10.1016/j.eja.2024.127288

Dai, Y., A. van Hooft, E. G. Patton, J. Boekee, S. van der Linden, M. C. ten Veldhuis, B. J. van de Wiel (2024). Integrated large-eddy simulation for modeling plant-tissue warming induced by wind machines in an orchard canopy. Agric. For. Meteorol. 356: 110175. doi.org/10.1016/j.agrformet.2024.110175

Kaya, O., C. Kose, A. Esitken, T. Gecim, V. Donderalp, S. Taskin, M. Turan (2021). Frost tolerance in apricot (*Prunus armeniaca* L.) receptacle and pistil organs: how is the relationship among amino acids, minerals, and cell death points?. Int. J. Biometeorol. 65: 2157-2170. doi.org/10.1007/s00484-021-02178-x

Kaur, A., Zhang, L., Maness, N. O., Ferguson, L., Graham, C. J., Sun, Y., Panta, S., Pokhrel, N., Yang, M. and Moss, J. Q. (2024). Dormant carbohydrate reserves enhance pecan tree spring freeze tolerance: controlled environment observations. Front. Plant Sci. 15, 1393305. https://doi.org/10.3389/fpls.2024.1393305

Mao, Y., X. Ji, Q. Meng, Z. Xu, Y. Yuan, Y., M. Li, L. Niu, Y. Zhang, D. Sun (2022). Contribution of anthocyanin and polyunsaturated fatty acid biosynthesis to cold tolerance during bud sprouting in tree peony. Ind. Crops Prod. 188: 115563. doi.org/10.1016/j.indcrop.2022.115563

KREI (Korea Rural Economic Institute) (2024). Agricultural outlook 2024: future of agriculture and rural communities with the people. KREI, Korea.

Lee, I. B., D. H. Jung, S. B. Kang, S. S. Hong, P. H. Yi, S. T. Jeong, J. M. Park (2023a). Changes in growth, fruit quality, and leaf characteristics of apple tree (*Malus domestica* Borkh. 'Fuji') grown under elevated CO2 and temperature conditions. Hortic. Sci. Technol. 41: 113-124. doi.org/10.7235/HORT.20230012

Lee, J. C., Y. S. Park, H. N. Jeong, J. H. Kim, J. Y. Heo (2023b). Temperature changes affected spring phenology and fruit quality of apples grown in high-latitude region of South Korea. Horticulturae. 9: 794. doi.org/10.3390/horticulturae9070794

Lee, J. C., M. Zebro, H. N. Jeong, J. Y. Heo (2025). Variation in flower frost tolerance among seven apple cultivars and transcriptome response patterns in two contrastingly frost-tolerant selected cultivars. Open Life Sci. 20: 20251107. doi.org/10.1515/boil-2025-1107

Melke, A. (2015). The physiology of chilling temperature requirements for dormancy release and bud-break in temperate fruit trees grown at mild winter tropical climate. J. Plant Stud. 4: 110–156. doi.org/10.5539/jps.v4n2p110

Navarro Villa, P (2025). Global production of fruit by variety selected 2023 https://www.statista.com/statistics/264001/worldwide-production-of-fruit-by-variety/ accessed 28 April 2025

Olszewski, F., P. Jeranyama, C. D. Kennedy, C. J. DeMoranville (2017). Automated cycled sprinkler irrigation for spring frost protection of cranberries. Agric. Water Manag. 189: 19-26. doi.org/10.1016/j.agwat.2017.04.014

Pan,Q., Y. Lu, H. Hu, Y. Hu (2024). Review and research prospects on sprinkler irrigation frost protection for horticultural crops. Sci. Hortic. 326: 112775. doi.org/10.1016/j.scienta.2023.112775

Pearce, R. S (2001). Plant freezing and damage. Ann. Bot. 87: 417-424. doi.org/10.1006/anbo.2000.1352

Pfleiderer, P., I. Menke, C. F. Schleussner (2019). Increasing risks of apple tree frost damage under climate change. Clim. Change. 157: 515-525. doi.org/10.1007/s10584-019-02570-y

Ribeiro, A. C., J. P. De Melo-Abreu, R. L. Snyder (2006). Apple orchard frost protection with wind machine operation. Agric. For. Meteorol. 141: 71-81. doi.org/10.1016/j.agrformet.2006.08.019

Rodrigo, J (2000). Spring frosts in deciduous fruit trees—morphological damage and flower hardiness. Sci. Hortic. 85: 155-173. doi.org/10.1016/S0304-4238(99)00150-8

Szalay, L., Z. György, M. Tóth (2019). Frost hardiness of apple (*Malus* X *domestica*) flowers in different phenological phases. Sci. Hortic. 253: 309-315. doi.org/10.1016/j.scienta.2019.04.055

Zebro, M., Kang, J., J. Y. Heo (2023). Effects of temperatures on pollen germination and pollen tube growth in apple. Bragantia. 82. e20220242. doi.org/10.1590/1678-4499.20220242.